

4.0 DEVELOPMENT OF SURFACE WATER MODEL

4.1 Methodology

The spreadsheet model used in the surface water impact analysis employs a steady-state, mass-balance approach to estimate steady-state concentrations of EC and SAR after two or more inflows are mixed. This steady-state approach is commonly used by states in EPA Region VIII to predict possible effects of point-source discharges on receiving waters. This approach has been endorsed in EPA guidance through the years (EPA 1991). The application of the mass-balance approach to SAR is supported by the analysis described in Appendix B.

4.2 Model Input Parameters

Input parameters to the model were developed from analysis of reasonably conservative assumptions as well as measures of central tendency (typical or mean values). Table 4-1 describes the input parameters and indicates whether conservative or mid-range values were used in the model for the impact analysis. A complete summary of the inputs used in the impact analysis for surface water quality is presented in Appendices C and D. The conservative assumptions (and the degree of conservatism they impart) are described below. Non-conservative (mid-range or mean value) assumptions also are described below. The resultant model is considered to provide a conservative, yet reasonable, estimate of the impacts of CBM development on surface water quality in the PRB.

Conservative assumptions:

- Mixed SAR was estimated using a simple flow-weighted mass balance equation, assuming SAR behaves as a constituent of water. This assumption results in overestimation of SAR and, potentially, of impacts by a factor of about 2 (see Appendix B).
- The maximum number of CBM wells based on reasonably foreseeable development in both Wyoming and Montana was used in the model.
- Impacts to streams were evaluated for 7Q10 flows as well as mean monthly flows. The 7Q10 flows are about a factor of 10 less than the mean monthly flow rates. The 7Q10 analysis evaluated the maximum likely impacts to surface water quality. (The 7Q10 is the minimum flow averaged over 7 consecutive days that is expected to occur on average, once in any 10-year period. The chance that the 7Q10 flow will occur in any year is 10 percent.)

Non-conservative (mid-range) assumptions:

- The model assumed complete mixing. Impacts to surface water quality may be greater than are predicted in the mixing zone near the points of discharge.
- Mean flow rates for CBM discharges were used in the model. Actual discharge rates vary by a factor of 10 or more.
- A typical value of channel loss was used in the model. This value would under-predict the impacts to surface water quality if discharge were piped directly to the river or if the discharge point is very close to the main stem river.

- Mean values for SAR and EC in CBM produced water by sub-watershed were used, while actual values within a sub-watershed vary by a factor of 2 for SAR and by a factor of 2 to 5 for EC.
- Mean values for ambient levels of SAR and EC in streams were used, while actual values for both parameters vary by a factor of 2 or more.

Table 4-1
Summary of Input Parameters

Parameter	Conservative Value	Typical Value	Magnitude of Range	Value Used in EIS
WY Estimated Number CBM Wells	RFD	---	---	Conservative
MT Estimated Number CBM Wells	RFD	---	---	Conservative
CBM Well Discharge Rate (gpm)	Max	Mean	10X	Typical (Mean)
Channel Loss (%)	0	20	10X	Typical (Mean)
CBM Produced Water EC (μS/cm)	Mean	Mean	2 to 5X	Typical (Mean)
CBM Produced Water SAR	Mean	Mean	2X	Typical (Mean)
Stream Flow (cfs)	7Q10	Mean	10X	Typical (Mean) & Conservative
Stream EC (μS/cm)	Low	Flow-weighted Mean	2X	Typical (Mean)
Stream SAR	High	Flow-weighted Mean	2X	Typical (Mean)

Note: μS/cm = Microsiemens per centimeter

gpm = Gallons per minute

RFD= Reasonable foreseeable development

7Q10 = The minimum flow averaged over 7 consecutive days that is expected to occur on average, once in any 10-year period.

4.2.1 Stream Quantity and Quality

4.2.1.1 Stream Flow

Wyoming

Representative flow rates for streams in the Wyoming portion of the PRB were estimated from analysis of the historical record at U.S. Geological Survey (USGS) stream gauging stations (Kuhn 2002). Statistics on flow were compiled from the mean of each month's flows. Values for 7Q10 flow were computed for stations with adequate record. These statistics on flow are summarized in Appendix C. The 7Q10 flow represented the minimum flow averaged over 7 consecutive days that would be expected to occur, on average, once in any 10-year period. Base-flow conditions in the streams were represented by the low of the mean monthly flows. The impact analysis for surface water quality evaluated the effects of CBM development on water quality using flows that ranged from a low corresponding to the 7Q10 flow statistic to a high represented by the maximum of the mean monthly flow.

Another flow regime to consider is the 1Q10 flow, which is the lowest daily flow to occur on average, once in every 10-year period. For most of the streams addressed in this analysis, there is no real difference between the 7Q10 and 1Q10 in terms of flow (almost always zero for both), however, there is an exception in the Tongue River. A number of the proposed EC and SAR values are absolute maximums, which would warrant the use of the 1Q10 flow parameter. However, WDEQ would not authorize any new CBM discharges to the Upper Tongue River sub-watershed unless the water quality of the discharge was similar to the ambient water quality in the Tongue River. In Montana, a similar reluctance is in place; the MDEQ will likely not authorize new discharges of untreated CBM water to the Tongue River watersheds except perhaps on a flow-based permit that would only allow discharge during high-flow periods. Therefore, an analysis using this flow regime has not been performed.

Montana

Representative flow rates for streams in the Montana portion of the PRB and adjacent areas were extracted from the historical data in the USGS archives of stream gauging stations (USGS 2002). Statistics on flow were assembled for mean monthly and 7Q10 flows. These statistics are summarized in Appendix C. Base-flow conditions for each gauging station were derived from the lowest of the monthly means. High flow conditions were derived from the maximum of the monthly means. The impact analysis for surface water quality modeled each of the monthly mean flow values and the 7Q10 rate computed. Potential impacts were evaluated using the base flow, high flow, and 7Q10 rates for each gauging station.

4.2.1.2 Stream Water Quality

Wyoming

EC and SAR values for streams in the Wyoming portion of the PRB were derived from analysis of the historical record at USGS stream monitoring stations (Kuhn 2002). The water quality constituents were plotted against stream flow, and power curves were fitted to the data to develop a mathematical relationship between flow and water quality (Meyer 2002a). The water quality data were compiled by the month and year when they were collected, and a mean of the values from each month was calculated. Representative SAR values were derived from the mean of sample SAR values, rather than from the mean of values for sodium, calcium, and magnesium from each sample. Either method for estimating mean SAR values yielded similar results (Appendix B). A comparison of the data projected by the power curve relationship at each monthly mean discharge versus the mean value for all water quality samples for the month indicated that neither method fully captured the natural variation of water quality attributable to changes in stream flow or seasonal fluctuations with time (Meyer 2002a). However, averaging the value computed using the power curve with the mean of the monthly water quality values appeared to yield the best approximation of water quality at mean monthly flow rates throughout the year (Meyer 2002a). Therefore, these average values were used in the water quality impact analysis as representative of stream water quality at the mean monthly discharge. Representative monthly water quality values are summarized in Appendix C.

Representative EC and SAR values for 7Q10 flows were estimated from the power curve analysis only. Both EC and SAR values were estimated for the Upper Powder River at Arvada for the month of September based on a very large difference between the power curve projection and the mean of the monthly values. EC values for 7Q10 flow were also estimated for the Middle Powder River at Moorhead because of an unrealistically large value projected by the power curve relationship.

Montana

EC and SAR values for streams in the Montana portion of the PRB and adjacent areas were derived from historic USGS monitoring data (USGS 2002). Monitoring data were aggregated by month to calculate mean monthly values for EC and SAR. The data were plotted against stream flow rates to derive water quality values for 7Q10 flows. Representative SAR values were estimated from the mean of sample SAR values rather than from the mean of the values for sodium, calcium, and magnesium from each sample. Either method for deriving mean SAR values yielded similar results (Appendix B). Representative monthly water quality values are summarized in Appendix C.

4.2.2 CBM Quantity and Quality

4.2.2.1 CBM Wells

Wyoming

This analysis was based on estimates of the number of potential new CBM wells, which is described by the BLM as the “Reasonable Foreseeable Development” (RFD). Projections for RFD of CBM in Wyoming under Alternatives 1, 2A, and 2B includes 39,367 new wells in the Wyoming portion of the PRB over the next 10 years. Under Alternative 3, the RFD includes 15,458 new wells over 10 years. The life of each producing well would be 7 years. These estimates of RFD are divided among the sub-watersheds. The number of wells that would produce in each sub-watershed during the peak year of water production is summarized in Appendix D.

Montana

Using the assumptions in the RFD and the extrapolated discharge trend line that estimated the average production rate for a specified time frame, it was determined that the maximum annual volume of produced water would occur in year six of the proposed development. During year six, 12,641 wells would be producing. The number of wells that would produce in each sub-watershed during the peak year of water production is summarized in Appendix D.

4.2.2.2 CBM Discharge Rate

Wyoming

The BLM analyzed water production data from existing wells downloaded from the WOGCC web page to project total water production on an annual and over the life of the project basis by sub-watershed (Meyer 2002b). Mean monthly water production by sub-watershed was plotted and visually examined to identify the point where maximum water production was reached and a decline in monthly water production could be observed. A logarithmic decline curve was fitted to the data points after maximum production ends, and the equation of the curve was computed and used to predict annual water production for a typical well in each sub-watershed. For the Antelope Creek sub-watershed, where sufficient production history was not available to produce a suitable decline curve, estimates of water production were based on the production history from the Upper Belle Fourche sub-watershed. Water production data for all existing wells in the Middle Powder, Upper Powder, Clear Creek, Crazy Woman Creek, and Salt Creek sub-watersheds were combined to compute a single decline curve, which was applied to all of

these sub-watersheds. Applying the average decline curve for the sub-watershed to the number of wells proposed for each year made it possible to project annual water production over the life of the project (Meyer 2002b). The year of peak water production was calculated from this analysis. The average discharge rate per well was estimated using the peak discharge in each sub-watershed divided by the total number of wells discharged in the peak year in each sub-watershed.

The number of wells and corresponding flow rate per well in the peak year of water production were used as input in the impact analysis for surface water quality for the Upper Belle Fourche, Antelope Creek, and the Upper Cheyenne River sub-watersheds. The average peak discharge rate in these sub-watersheds is 7.0, 11.9, and 9.6 gpm/well, respectively. A value of 6.2 gpm/well, which represents a basin-wide (WY and MT) average production rate during the peak year of water production was used in the Powder River, Little Powder River, and Upper Tongue River sub-watersheds to facilitate a parallel analysis of impacts to water quality from CBM development in both states.

Montana

Discharge rates for CBM produced water used in the model were derived by estimating the highest water production rate for all wells proposed for the Montana portion of the PRB. This estimate was a combination of the projected number of active CBM wells according to the RFD, concatenated against the calculated decline curve for water production (ALL 2001). The result of the forecasts and calculations show that the Montana portion of the PRB would contain 12,641 CBM wells during the sixth year of CBM development. In addition, the average well would produce water at rate of 6.2 gpm, for a total of 5.4 billion cubic feet produced during that year. The total wells were assigned to specific sub-watersheds to project the total rate of water production that would be discharged to the main stem streams or managed by other options.

4.2.2.3 CBM Water Quality

Wyoming

The BLM summarized and modeled EC and SAR values for CBM produced water from 132 wells by sub-watershed (Meyer 2002c). EC and SAR values were derived from the chemical analysis from each well. Universal Transverse Mercator (UTM) coordinates were assigned to each sample point, and the data were imported into contouring software for analysis. Kriging was employed to transform the irregularly spaced sample points into a grid of uniform spacing over the entire PRB (Meyer 2002c). Grid points were then exported as X-Y-Z coordinates to allow spatial analysis and data interpretation using ArcView (Meyer 2002c). Grid points were imported into ArcView and clipped to the approximate outcrop of the Wyodak-Anderson coal zone. The grid points were intersected with an overlay that contained the boundaries of the sub-watershed. Mean EC and SAR values were calculated from the sub-watershed grid points. Analysis of the extracted points yielded a basin-weighted value because uniform grid spacing was applied to the entire basin (Meyer 2002c).

The EC and SAR values used in the analysis of impacts to water quality in the Upper Cheyenne River sub-watershed were calculated using a flow-weighted average of the combined discharges from the Antelope Creek and Upper Cheyenne River sub-watersheds. The EC and SAR values used in the analysis of impacts to water quality in the Middle Powder River sub-watershed were calculated using a flow-weighted average of the combined discharges from the Salt Creek, Clear Creek, Crazy Woman Creek, Upper Powder River, and Middle Powder River sub-watersheds. The CX Ranch data that represented the

high-end value for EC and SAR were used for the Montana contribution at the state line stations in the Middle Powder and the Upper Tongue.

Montana

The quality of CBM produced water used in the model was derived on a sub-watershed basis. Limited data on the quality of CBM water were available for Montana; the CX Ranch field located near Decker, Montana, was the only source of data on CBM produced water in the state. Future CBM development may produce water of different chemistry and quality. Therefore, a range of water quality values was used in the model to cover the range of possible water quality conditions that may be encountered in the Montana portion of the PRB.

For the Tongue River, Bighorn/Little Bighorn, and Rosebud Creek sub-watersheds, the range of water quality values included mean values from the CX Ranch field (SAR = 47, EC = 2,207 $\mu\text{S}/\text{cm}$), to mean values from the Upper Tongue River sub-watershed in Wyoming (SAR = 38.7, EC = 2,406 $\mu\text{S}/\text{cm}$). For the Powder River, Mizpah Creek, and the Lower Yellowstone sub-watersheds, the range of values included the Wyoming mean to the Wyoming maximum. These values are summarized in Appendix D.

4.2.3 Water Losses

4.2.3.1 Managed Water Loss

Wyoming

Water produced from CBM wells and managed through containment, LAD, and injection would not have direct effects on quality and quantity of surface water, because, by definition (see chapter 2, WY FEIS) none of the discharged water under these water handling options would reach drainages in the sub-watersheds. This analysis assumed that CBM produced water that would be actively treated would be 100 percent consumptively used because of the higher quality.

The percentage of CBM water production handled by active treatment, containment, LAD, and injection, and the proportion of water lost to the shallow aquifer system from infiltration impoundments, are summarized collectively as Managed Water Loss (MWL). Managed water losses include beneficial use. The percentage of CBM produced water included in the MWL varies by alternative and among sub-watersheds. These values are summarized in Appendix D.

Montana

This analysis assumed that CBM produced water would be managed in two ways: discharge to the surface, which was assumed to reach the main stem streams in each sub-watershed; and management using other options, which was assumed not to reach the main-stem streams. Under surface discharge, the analysis assumed that 20 percent of the volume would be lost to infiltration, evaporation, uptake by plants, and local beneficial uses. In the model, MWL would include impoundments, treatment and use, injection, and other industrial uses, such as in coal mining operations. The proportion of produced water discharged to the surface and the percentage of MWL vary by alternative and among the various sub-watersheds. These values are summarized in Appendix D.

4.2.3.2 Conveyance Loss

Conveyance loss includes evaporative and infiltration losses. Infiltration into soil typically comprises approximately 20 percent of precipitation in a watershed for arid and semi-arid regions (Stephens and Knowlton 1986). This analysis assumed that this value would represent loss in overland flow, and thus, was used as a minimum conveyance loss in the surface water model. The conveyance loss was applied to the proportion of CBM water discharged directly to the surface and to the proportion of CBM produced water discharged to infiltration impoundments that was assumed to resurface and contribute to existing surface flows. In addition, this analysis uses conveyance loss synonymously with “in-channel loss.” Higher rates of infiltration combined with some evaporative losses would result in a smaller fraction of the discharges of CBM produced water that would reach the main stems.

4.3 Assumptions

The following assumptions form the framework for analyzing the impacts in this document:

- Discharge of CBM produced water to surface drainages is assumed to result in a conveyance loss of 20 percent. This value is considerably lower than the values derived from studies of surface water losses in creek flows within several drainages of the Wyoming portion of the PRB (Meyer 2000, Applied Hydrology and Associates 2001a). The remaining 80 percent of the CBM produced water discharged to surface drainages is assumed to reach the main stem in each sub-watershed.
- Where produced water is discharged to infiltration impoundments designed to allow infiltration, 15 percent of the water would resurface and contribute to in-channel flow; the remainder would infiltrate into the shallow aquifer system.
- It is assumed that the sodium and salinity in water produced from CBM wells are the target constituents that control the usefulness of the water for crop irrigation. Irrigation is the primary beneficial use for the majority of water resources in the sub-watersheds expected to have the greatest potential for CBM development, especially in the Montana portion of the Powder River Basin. Sodium causes osmotic stress to plants and destroys the texture of clayey soils; these combined effects make sodium content, and especially SAR, a point of emphasis when impacts to water resources from CBM water are evaluated. The salinity of irrigation water, as expressed by EC, affects crop productivity. This analysis defined the irrigation season as the period from April 1 through October 31.
- The impact analysis did not consider changes in water quality that may occur as the CBM discharge flows overland toward the main stem streams or as it infiltrates to shallow groundwater systems and is discharged to surface flows. Results from monitoring water quality and flow from the tributary monitoring program suggest that CBM discharges tend to accumulate salts (EC) from the soils and alluvium as they flow down tributary channels and that SAR values decrease (Applied Hydrology and Associates 2001b). Thus, CBM discharges improve with respect to SAR but worsen with respect to EC between the discharge point and the receiving stream. Therefore, using the water quality of the CBM discharge provides a more conservative estimate of the impact on surface water of the main stems.
- The impact analysis did not consider values for individual constituents (sodium, magnesium, and calcium) in determining the resultant SAR values. This assumption is inherently conservative and is discussed in greater detail in Appendix B.